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SuperMariah:
A Similarity-based Method for Determining Wind, Temperature, and Humidity Profile Structure in the Surface Boundary Layer

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ARL-TR-264 June 1994

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
June 1994

3. REPORT TYPE AND DATES COVERED
Final

4. TITLE AND SUBTITLE
SuperMariah: A Similarity-based Method for Determining Wind, Temperature, and Humidity Profile Structure in the Surface Boundary Layer

5. FUNDING NUMBERS

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
Battlefield Environment Directorate
Attn: AMSRL-BE-W
White Sands Missile Range, New Mexico 88002-5501

8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-TR-264

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
2800 Powder Mill Road
Adelphi, MD 20783-1145

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
ARL-TR-264

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE
A

13. ABSTRACT *(Maximum 200 words)*

SuperMariah is a new methodology for estimating the surface layer similarity scaling constants for wind, temperature, and specific humidity, using data from tower-borne sensors. It is conceptually based on the Dynamic Similarity of Flows Theory. We discuss the origin and logic of the Mariah approach (the predecessor of SuperMariah) and then present the extension of Mariah resulting in SuperMariah. This report reviews the complete set of model equations and presents several examples to illustrate comparisons of the Mariah, SuperMariah, and the more traditional O'KEYPS formulations.

14. SUBJECT TERMS
micrometerology, Obukhov similarity, surface boundary layer, O'KEYPS function, temperature, specific humidity, wind speed

15. NUMBER OF PAGES
35

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	SAR

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

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1. Introduction

Obukhov [1] determined that the surface boundary layer could be characterized by a unique scaling length, L, which would represent the surface layer's depth. Monin and Obukhov [2] generalized the Dynamic Similarity of Flows Theory with the introduction of the concept of the scaling ratio, z/L, and the log-linear wind and temperature profiles for a stable atmosphere. Panofsky et al. [3] partially extended the similarity approach to the unstable regime. However, Panofsky [4] provided the insight that led to the present day linear-quartic vertical shapes of the wind, temperature, and specific humidity profiles in the surface boundary layer.

The linear-quartic approach was dubbed the KEYPS* function using the initials of the participating inventors. Yaglom [5] changed this acronym to O'KEYPS, adding Obukhov's efforts of 1946 to the original five papers.

Obukhov did not originally consider the effects of water vapor on atmospheric stability or upon the structure of atmospheric turbulence. This omission was rectified by Busch. [6] Paulson [7] suggested a simple workable solution for establishing the diabatic influence functions but Nickerson, Smiley, [8] and Benoit [9] finalized this approach.

Rachele et al. [10] developed what is known as the Mariah equations whereby the Obukhov [1] length could be established from the measured gradients. This simplification eliminated the laborious, iterative process of calculating the diabatic influence functions to solve the wind, temperature, and specific humidity profile equations to obtain the scaling constants u^*, θ^*, and q^* that are necessary components of the surface energy balance equations. The widely used approach is to choose trial values of the parameters, then cycle through an iterative process until the solution converges. The intent of this report is to further extend the Mariah model to what is referred to as the SuperMariah approach.

**Kazanski and Monin (1956), Ellison (1957), Yamamoto (1959), Panofsky (1963), and Sellers (1962).*

2. Mariah

The Mariah approach was based upon the premise that the similarity scaling constants for unstable flow can be written as

$$u^* = \frac{k\,\Delta v}{\phi_m\,\Delta \ln z} \tag{1}$$

$$\theta^* = \frac{k\,\Delta \theta}{\phi_h\,\Delta \ln z} \tag{2}$$

$$q^* = \frac{k\,\Delta q}{\phi_h\,\Delta \ln z} \tag{3}$$

where

u^*	=	friction velocity
k	=	Karman's constant
v	=	horizontal wind speed
z	=	height above surface
θ^*	=	scaling temperature
θ	=	mean potential temperature
q^*	=	scaling humidity
q	=	specific humidity
ϕ_m	=	dimensionless wind shear
ϕ_h	=	dimensionless lapse rate.

ϕ_m and ϕ_h are functionally defined later. ϕ_h appears in both equations (2) and (3) since the similarity theory assumes that heat and mass transfer are identical.

When evaluating the above similarity constants we [11] found, using the mean value theorem of calculus test, that the gradients for each layer are tangent to the indicated profile at the height

$$z^{*} = \frac{\Delta z}{\Delta \ln z} \tag{4}$$

instead of the geometric height which is generally assumed.

The scaling length L is given by

$$L = \frac{u^{*2}\,\theta_{vl}}{k\,g\,\theta_{v}^{*}} \tag{5}$$

where

θ_{v1} = virtual potential temperature at reference height

$$\theta_{vl} = \theta_{1}\,(1.0 + 0.61\,q) \tag{6a}$$

g = acceleration of gravity

θ_{v}^{*} = virtual scaling constant defined as.

$$\theta_{v}^{*} = \theta^{*} + 0.61\,\theta_{1}\,q^{*}. \tag{6b}$$

Substitution of equations (1), (2), (3), (6a), and (6b) into equation (5) yields

$$L = \frac{\theta_{vl}\,\phi_{h}\,(\Delta v)^{2}}{g\,\phi_{m}^{2}\,(\Delta\theta + 0.61\,\theta_{1}\,\Delta q)\,\Delta \ln z} \tag{7}$$

as the expression for L. For unstable ($z/L < 0$) conditions,

$$\phi_m = \left(1 - 15\,\frac{z^*}{L}\right)^{-1/4} \quad and \quad \phi_h = \left(1 - 15\,\frac{z^*}{L}\right)^{-1/2} \tag{8a,b}$$

and for stable ($z/L > 0$) conditions,

$$\phi_m = \phi_h = 1 + \beta\,\frac{z^*}{L} \;. \tag{8c}$$

Since in the unstable regime $\phi_h = \phi_m^2$, equation (7) simplifies to

$$L = \frac{\theta_{vl}\,(\Delta v)^2}{g\,(\Delta\theta + 0.61\,\theta_1\,\Delta q)\,\Delta \ln z} \;. \tag{9}$$

In stable flow conditions where $\phi_h = \phi_m = (1 + \beta\, z/L)$, equation (7) becomes

$$L = \frac{\theta_{vl}\,(\Delta v)^2}{g\,\phi_m\,(\Delta\theta + 0.61\,\theta_1\,\Delta q)\,\Delta \ln z} \;. \tag{10}$$

Equation (10), after some additional manipulation (see appendix A), becomes

$$L = \frac{B^2}{60\,z^* + 2B} \tag{11}$$

where

$$B = \frac{2\,\theta_{vl}\,(\Delta v)^2}{g\,(\Delta\theta + 0.61\,\theta_1\,\Delta q)\,\Delta \ln z} \;. \tag{12}$$

Although simple and efficient, the Mariah parameters must be smoothed and averaged with height in order to invoke forced stationarity upon the vertical profiles in agreement with the tenets of similarity. This vertical smoothing and averaging is discussed in the next section.

3. SuperMariah

SuperMariah is an extension of Mariah. First, we determine if atmospheric conditions are stable, unstable, or neutral depending on whether the potential temperature with height is adiabatic, superadiabatic, or subadiabatic. After determining the stability condition, we then use the Mariah equation for computing L using equation (9) for the unstable case or equation (13) for stable conditions. Having L, we can compute u^*, θ^*, and q^* for different combinations of measured values of wind, temperature, and specific humidity from all tower or mast levels.

The sets of u^*, θ^*, and q^* from all these combinations are then averaged resulting in a single estimate of each similarity constant for the total profile height.

The average values of u^*, θ^*, and q^* are inserted into equation (4) to obtain a new value of L. This estimate of L is then used to compute new values of the scaling constants. This process is repeated until all constants converge, usually requiring 3 to 8 iterations based on the following:

1. The Obukhov length changes by less than 0.001 m from one iteration to the next. In rare cases, the calculated value of L decreases at each step and may become smaller than the convergence test, whereupon the results are deemed invalid.

2. An arbitrary number of steps has been completed with no convergence. In this case, results are also invalid.

Upon successful convergence, the similarity profiles for wind speed, temperature, and specific humidity are calculated from the scaling constants and Obukhov length obtained (figures 1 and 2). In the following equations, a subscript r indicates a value at the reference height while a subscript n indicates the value at height z_n.

For stable cases

$$\nu = \nu_r + \frac{u^*}{k}\gamma \qquad (13)$$

$$\theta = \theta_r + \frac{\theta^*}{k}\gamma \tag{14}$$

$$q = q_r + \frac{q^*}{k}\gamma \tag{15}$$

where

$$\gamma = \ln\left(\frac{z_n}{z_r}\right) + 5.0\,\frac{z_n - z_r}{L}. \tag{16}$$

For unstable cases

$$v = v_r + \frac{u^*}{k}\left[\ln\left(\frac{x-1}{x+1}\right) + 2\tan^{-1}(x)\right] \tag{17}$$

$$\theta = \theta_v + \frac{\theta^*}{k}\ln\left(\frac{y-1}{y+1}\right) \tag{18}$$

$$q = q_r + \frac{q^*}{k}\ln\left(\frac{y-1}{y+1}\right) \tag{19}$$

where

$$x = \left(1 - 15\,\frac{z_n}{L}\right)^{1/4} \tag{20}$$

$$y = \left(1 - 15\,\frac{z_n}{L}\right)^{1/2}. \tag{21}$$

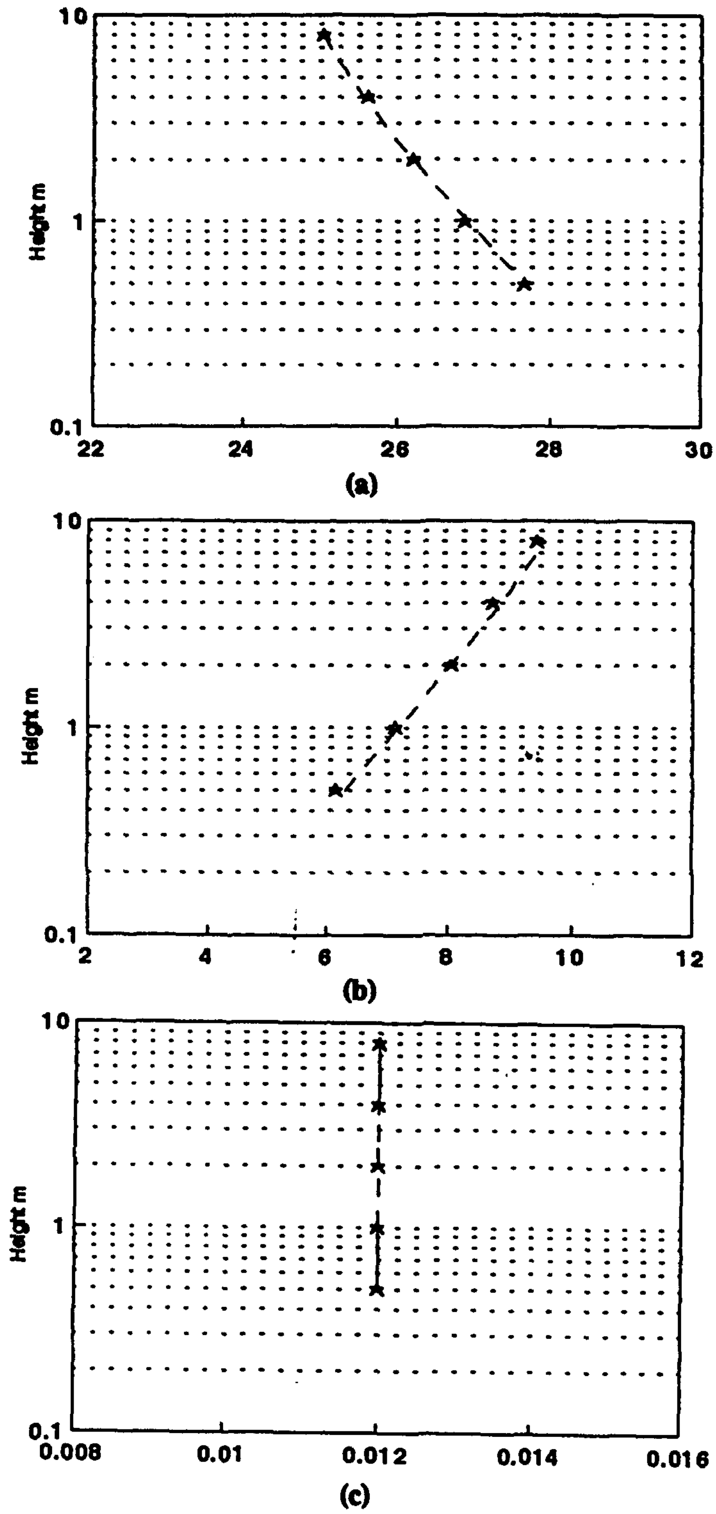

Figure 1. SuperMariah calculated profiles compared to data from REBAL '92: 9 July 1992 1000 CST unstable flow. (a) Temperature where $\theta^* = -.4856$, (b) Wind speed where $u^* = .544$, (c) Specific humidity where $q^* = -5.335 * 10e\text{-}5$.

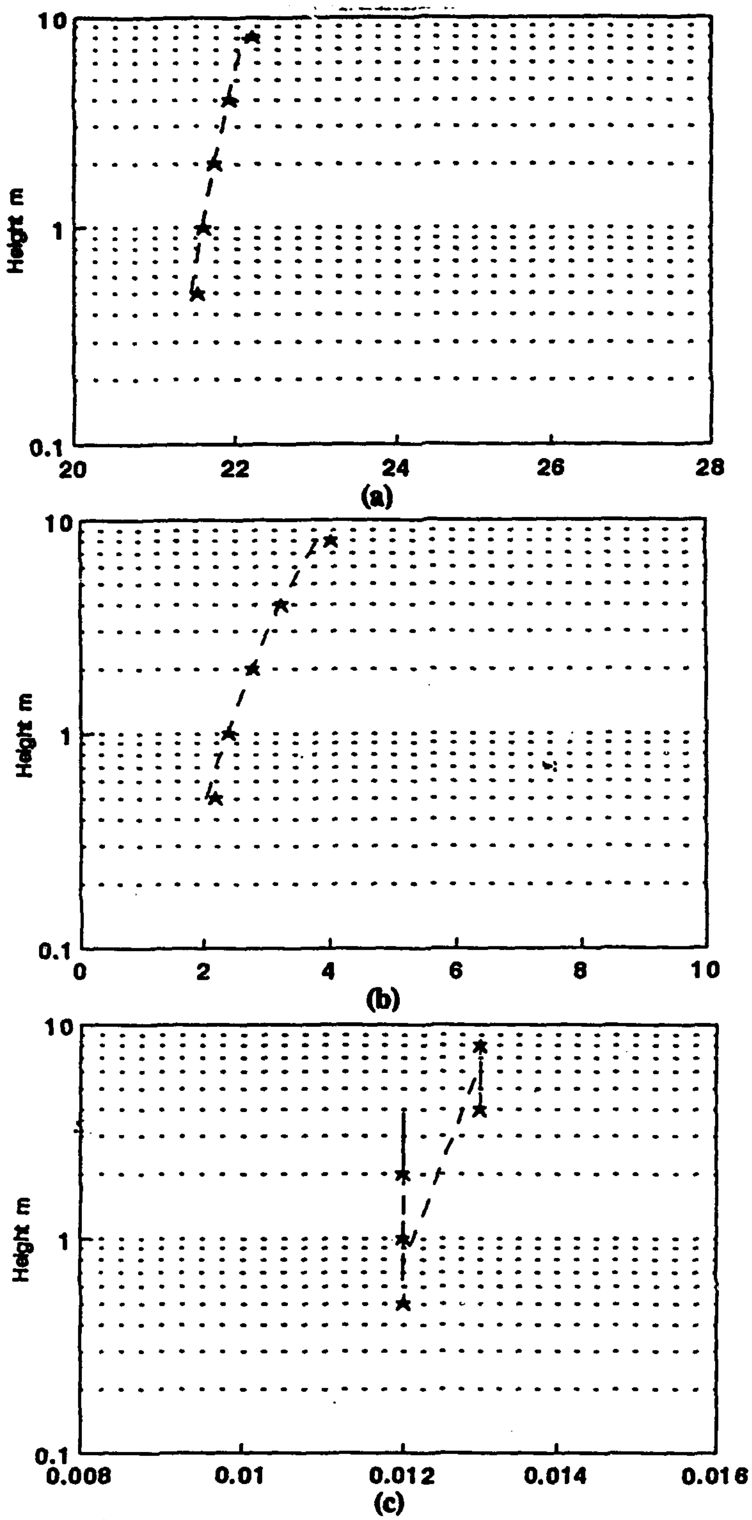

Figure 2. SuperMariah calculated profiles compared to data from REBAL' 92: 15 July 1992 2245 CST stable flow. (a) Temperature where θ^* = .0742, (b) Wind speed where u^* = .184, (c) Specific humidty where q^* = 1.474 * 10e-5.

4. The SuperStar Option

Experience has shown that the vertical profile of wind, potential temperature, and specific humidity obtained by the SuperMariah procedure may be rotated slightly to the left or the right of the measured data points. These profiles can be adjusted using equations tailored from a paper by Rachele and Tunick. [12] The approach requires that adjustment increments Δv, $\Delta\theta$, and Δq be estimated, usually by taking the difference between the highest tower level data values (or the tower data level the user has the most confidence in) and the corresponding calculated value at that level, z_n. These differences are then used in adjustment matrices resulting in modifications to scaling parameters for wind, potential temperature, and specific humidity, i.e., Δu^*, $\Delta\theta^*$, and Δq^*. The procedure for one case is demonstrated in figure 3.

The correction matrix for stable conditions is

$$\begin{vmatrix} A + \dfrac{2b_v L}{u^*} & -\dfrac{b_v L}{\theta_v^*} & -\dfrac{.61\,\theta_r b_v L}{\theta_v^*} \\ \dfrac{2b_t L}{u^*} & A - \dfrac{b_t L}{\theta_v^*} & -\dfrac{.61\,b_t L \theta_r}{\theta_v^*} \\ \dfrac{2b_q L}{u^*} & -\dfrac{b_q L}{\theta_v^*} & A - \dfrac{.61\,b_q L \theta_r}{\theta_v^*} \end{vmatrix} \begin{vmatrix} \Delta u^* \\ \Delta\theta^* \\ \Delta q^* \end{vmatrix} = \begin{vmatrix} \Delta v \\ \Delta\theta \\ \Delta q \end{vmatrix} \tag{22}$$

where

$$A = \frac{1}{k}\left[\ln\left(\frac{z_n}{z_r}\right) + 5\left(\frac{z_n - z_r}{L}\right)\right] \tag{23}$$

$$b_v = -5u^*\left(\frac{z_n - z_r}{kL^2}\right) \tag{24}$$

$$b_t = -5\theta^*\left(\frac{z_R - z_r}{k L^2}\right) \tag{25}$$

$$b_q = -5q^*\left(\frac{z_R - z_r}{k L^2}\right). \tag{26}$$

The correction matrix for unstable conditions is

$$\begin{vmatrix} \dfrac{v_R - v_r}{u^*} & 0.0 & 0.0 & C_{14} \\ 0.0 & \dfrac{\theta_R - \theta_r}{\theta^*} & 0.0 & C_{24} \\ 0.0 & 0.0 & \dfrac{q_R - q_r}{q^*} & C_{34} \\ \dfrac{2L}{u^*} & -\dfrac{L}{\theta_v^*} & 0.0 & 1.0 \end{vmatrix} \begin{vmatrix} du^* \\ dt^* \\ dq^* \\ dL \end{vmatrix} = \begin{vmatrix} \Delta v \\ \Delta t \\ \Delta q \\ 0.0 \end{vmatrix} \tag{27}$$

where

$$C_{14} = \frac{15\,u^*}{k L^2}\left(\frac{z_R}{x_2\,(x_2^4 - 1)} - \frac{z_r}{x_1\,(x_1^4 - 1)}\right) \tag{28}$$

$$C_{24} = \frac{15\,\theta^*}{k L^2}\left(\frac{z_R}{y_2\,(y_2^2 - 1)} - \frac{z_r}{y_1\,(y_1^2 - 1)}\right) \tag{29}$$

$$C_{34} = \frac{15\, q^{*}}{k\, L^{2}} \left(\frac{z_{n}}{y_{2}\, (y_{2}^{2} - 1)} - \frac{z_{r}}{y_{1}\, (y_{1}^{2} - 1)} \right) \tag{30}$$

$$x_{1} = \left(1 - \frac{15\, z_{r}}{L} \right)^{1/4} \tag{31}$$

$$x_{2} = \left(1 - \frac{15\, z_{n}}{L} \right)^{1/4} \tag{32}$$

$$y_{1} = \left(1 - \frac{15\, z_{r}}{L} \right)^{1/2} \tag{33}$$

$$y_{2} = \left(1 - \frac{15\, z_{n}}{L} \right)^{1/2}. \tag{34}$$

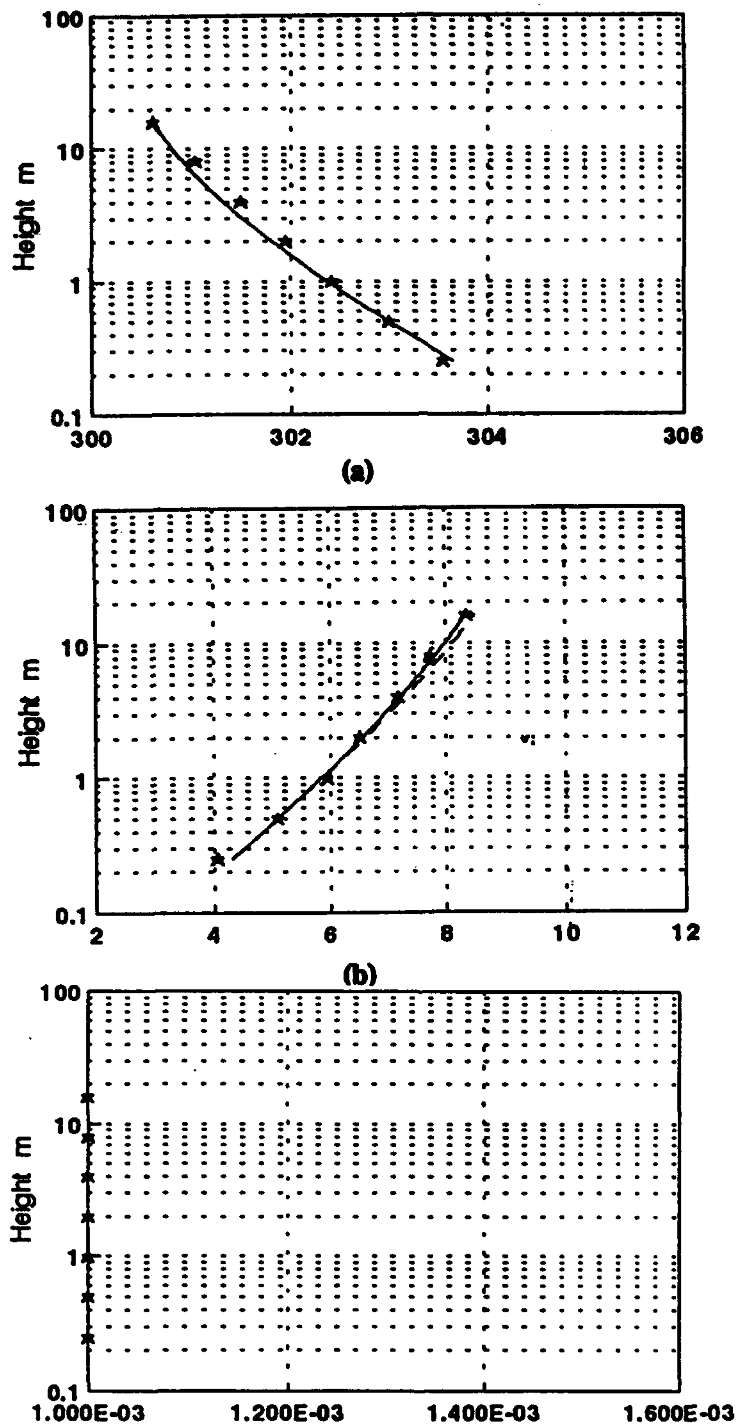

Figure 3. Comparison of SuperMariah and SuperStar profiles, Nebraska 7 August 1956 1205 CST (Lettau, 1957). (a) Potential temperature where SuperMariah θ^* = -.3989, Superstar θ^* = -.4024, (b) Wind speed where SuperMariah u^* = .4741, SuperStar u^* = .4578, (c) Specific humidity where SuperMariah q^* = -1.185e-5, SuperStar q^* = -1.117e-5.

5. Discussion

The SuperMariah solution, although iterative, is simpler to execute than the O'KEYPS plus Benoit [9] approach or the trial value iteration scheme using the O'KEYPS model. It also yields superior results, particularly if large amounts of data are being processed. Tunick et al. [13] utilized SuperMariah to process the REBAL '92 data sets (see Tunick et al. [14]) with outstanding results.

The actual algorithm is quite simple and is fast running. A comparative example for unstable flow of Mariah, SuperMariah and the O'KEYPS approach is given in table 1. It must be remembered that the O'KEYPS does not consider the effects of water vapor upon atmospheric stability and is based on the premise that $z/L = R$ in an unstable atmosphere. Thus, the gradient Richardson [15] numbers were first calculated. In order to provide the best estimate for the Monin-Obukhov [2] scaling ratio, the concept of the approximation of the height derivative of R was invoked. Lettau [16] was the first to suggest this approach, which may be written as

$$L^{-1} = \frac{\sum (R_i) z_i}{\sum z_i} ; \quad i = 1, 2, 3, \ldots \tag{35}$$

Both the Mariah and O'KEYPS data were subjected to the forced stationarity function of equation (35).

A similar comparison for the stable regime was made and is shown in table 2. For the log-linear O'KEYPS solution, it was assumed that

$$\phi_m = 1 + 15 R_i \tag{36}$$

$$\frac{z}{L} = R_i \phi_m = R_i (1 + 15 R_i) \tag{37}$$

with

$$L^{-1} = \frac{\sum \frac{z}{L}}{\sum z} \tag{38}$$

all based upon results obtained by Hansen. [17]

The data used to examine the unstable case included the REBAL sample for 1000 CST, 9 July 1992. All the calculated parameters are in agreement with the exception of the specific humidity scaling parameter, q^*, that shows up as a variable in the Mariah and O'KEYPS solutions. This departure from the norm (i.e., a constant q^* with height) is due to the REBAL experiment being conducted over bare soil. The evaporation rate over bare soil is radically different than what would be found over a vegetated surface. As a consequence, the specific humidity profiles and vertical gradients were not entirely in equilibrium with the surface.

An examination of the nocturnal data of table 2 for 2245 CST, 15 July 1992, indicates nonequilibrium specific humidity profiles and gradients. The specific humidity profile had inverted, a condition necessary for dew fall, but neither the relative humidity nor the gradients were sufficient to cause dew.

Table 1. Comparison of SuperMariah, Mariah, and O'KEYS schemes using REBAL data for 9 July 1992 1000 CST unstable flow

	raw data			SuperMariah data			SuperMariah parameters				
z^a	v^b	$temp^c$	q^d	v	temp	q	L^e	z/L	u^{*f}	θ^{*g}	q^{*h}
0.5	6.15	27.66	1.181	6.30	27.65	1.19	-46.12	-.0108	.544	-.4856	-5.335
1.0	7.14	26.87	1.176	7.19	26.88	1.18	-46.12	-.0217	.544	-.4856	-5.335
2.0	8.05	26.20	1.172	8.05	26.18	1.172	-46.12	-.0434	.544	-.4856	-5.335
4.0	8.72	25.62	1.16	8.85	25.55	1.165	-46.12	-.867	.544	-.4856	-5.335
8.0	9.43	25.04	1.154	9.58	25.02	1.159	-46.12	-.1735	.544	-.4856	-5.335

[a]height, z, in m
[b]wind speed, v, in m/s
[c]temperature in °C
[d]specific humidity, q, in (g/g) x 10^2
[e]Obukhov length, L, in m
[f]u^* in m/s
[g]θ^* in °C
[h]q^* in (g/g) x 10^3

Table 1. Comparison of SuperMariah, Mariah, and O'KEYS schemes using REBAL data for 9 July 1992 1000 CST unstable flow (continued)

	Mariah parameters from raw data					from smoothed data				
z^a	L^b	z/L	u^{*c}	θ^{*d}	q^{*e}	L	z/L	u^*	θ^*	q^*
1.0	-54.31	-.0184	0.583	-0.471	-2.937	-44.64	-.0284	0.589	-0.482	-3.005
2.0	-44.33	-.0451	0.519	-0.456	-5.978	-44.64	-.419	0.519	-0.456	-5.972
4.0	-42.78	-.0994	0.536	-0.501	-8.191	-44.64	-.0897	0.528	-0.487	-7.949
average	-47.14		0.546	-0.476	-5.709	-44.64		0.545	-0.475	-5.642

[a]height, z, in m
[b]Obukhov length, L, in m
[c]u^* in m/s
[d]θ^* in °C
[e]q^* in (g/g) x 10^3

Table 1. Comparison of SuperMariah, Mariah, and O'KEYS schemes using REBAL data for 9 July 1992 1000 CST unstable flow (continued)

	O'KEYS parameters from raw data					from smoothed data				
z^a	L^b	z/L	u^{*c}	θ^{*d}	q^{*e}	L	z/L	u^*	θ^*	q^*
1.0	-55.25	-.0181	.582	-.470	-2.932	-45.45	-.0220	.589	-.481	-2.998
2.0	-45.05	-.0444	.518	-.455	-5.959	-45.45	-.0440	.517	-.454	-5.948
4.0	-43.76	-.0914	.530	-.489	-7.993	-45.45	-.0897	.527	-.484	-7.904
average	-48.02		.543	-.471	-5.628	-45.45		.544	-.473	-5.617

[a]height, z, in m
[b]Obukhov length, L, in m
[c]u^* in m/s
[d]θ^* in °C
[e]q^* in (g/g) x 10^3

Table 2. Comparison of SuperMariah, Mariah, and O'KEYS schemes using REBAL data for 15 July 1992 2245 CST stable flow

	raw data			SuperMariah data			SuperMariah parameters				
z^a	v^b	$temp^c$	q^d	v	temp	q	L^e	z/L	u^{*f}	θ^{*g}	q^{*h}
0.5	2.19	21.54	1.246	2.04	21.48	1.2240	33.27	.0150	.184	.0742	1.474
1.0	2.40	21.61	1.244	2.40	21.61	1.2429	33.27	.0301	.184	.0742	1.474
2.0	2.78	21.74	1.246	2.78	21.74	1.2460	33.27	.0601	.184	.0742	1.474
4.0	3.25	21.94	1.258	3.24	21.89	1.2496	33.27	.1202	.184	.0742	1.474
8.0	4.04	22.21	1.258	3.83	22.07	1.2544	33.27	.2404	.184	.0742	1.474

[a]height, z, in m
[b]wind speed, v, in m/s
[c]temperature in °C
[d]specific humidity, q, in (g/g) x 10^2
[e]Obukhov length, L, in m
[f]u^* in m/s
[g]θ^* in °C
[h]q^* in (g/g) x 10^5

Table 2. Comparison of SuperMariah, Mariah, and O'KEYS schemes using REBAL data for 15 July 1992 2245 CST unstable flow (continued)

	Mariah parameters from raw data					from smoothed data				
z^a	L^b	z/L	u^{*c}	θ^{*d}	q^{*e}	L	z/L	u^*	θ^*	q^*
1.0	16.96	.0590	.106	.0384	7.1628	26.25	.0381	.118	.0430	8.018
2.0	23.74	.0842	.137	.0577	2.2485	26.25	.0762	.141	.0597	2.327
4.0	32.36	.1236	.179	.0752	1.7069	26.25	.1525	.167	.0699	1.587
average	24.35		.141	.0571	3.7061	26.25		.142	.0575	3.977

[a]height, z, in m
[b]Obukhov length, L, in m
[c]u^* in m/s
[d]θ^* in °C
[e]q^* in (g/g) x 10^3

Table 2. Comparison of SuperMariah, Mariah, and O'KEYS schemes using REBAL data for 15 July 1992 2245 CST unstable flow (continued)

	O'KEYS parameters from raw data					from smoothed data				
z^a	L^b	z/L	u^{*c}	θ^{*d}	q^{*e}	L	z/L	u^*	θ^*	q^*
1.0	24.69	.0405	.117	.0424	7.8999	29.72	.0336	.122	.0443	8.2491
2.0	25.87	.0773	.141	.0595	2.3167	29.72	.0673	.147	.0620	2.4142
4.0	33.98	.1177	.182	.0765	1.7354	29.72	.1346	.174	.0730	1.6576
average	28.18		.147	.0595	3.984	29.72		.148	.0598	4.1070

[a] height, z, in m
[b] Obukhov length, L, in m
[c] u^* in m/s
[d] θ^* in °C
[e] q^* in (g/g) x 10^3

6. Conclusions

The methods presented in this report are new, although based on traditional concepts of Dynamic Similarity. We have shown that similar results may be obtained by using the O'KEYPS, Mariah, or SuperMariah approaches. It is clear that the core of the SuperMariah methodology is based upon the computation of similarity scaling constants using the differences in the tower-based measurements of wind speed, temperature, and moisture (i.e., Mariah).

The advantages of employing the SuperMariah model are numerous. Primarily, the model executes quickly. Secondly, one has the capability of using as many or as few levels of tower data as are available. Additionally, SuperMariah outputs averaged values for the similarity scaling constants which represent many subintervals of tower measurements. Finally, the principle similarity premise of stationarity is preserved. This is too often neglected in micrometeorological tower data analyses schemes.

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Appendix A

Obukhov Length for Stable Conditions

The Obukhov length for stable conditions can be written as

$$L = \frac{\theta_{vl}\,(\Delta v)^2}{g\,\phi_m\,(\Delta\theta + 0.61\,\theta_1\,\Delta q)\,\Delta \ln z} \qquad \text{(A-1)}$$

or

$$L\phi_m = \frac{\theta_{vl}\,(\Delta v)^2}{g\,(\Delta\theta + 0.61\,\theta_1\,\Delta q)\,\Delta \ln z}. \qquad \text{(A-2)}$$

From Hansen*

$$\Phi_m = 1 + \beta\frac{z^*}{L} \qquad \text{(A-3)}$$

where

$$\beta = \frac{15}{\phi_m}\ . \qquad \text{(A-4)}$$

Substituting equation (A-4) into (A-3) and solving for ϕ_m gives

$$\phi_m = \frac{1 \pm \left[1 + 60\frac{z^*}{L}\right]^{1/2}}{2}\ . \qquad \text{(A-5)}$$

*Hansen, F. V., 1977: *The Critical Richardson Number.* ECOM-5829, U.S. Army Atmospheric Sciences Laboratory, White Sands Missile Range, NM 88002-5501.

Substituting equation (A-5) into (A-2) results in

$$L \pm L\left(1 + 60\frac{z^*}{L}\right)^{1/2} = \frac{2\,\theta_{vl}\,(\Delta v)^2}{g\,(\Delta\theta + 0.61\,\theta_1\,\Delta q)\,\Delta \ln z} = B \tag{A-6}$$

or

$$\pm L\left(1 + 60\frac{z^*}{L}\right)^{1/2} = B - L\ . \tag{A-7}$$

Squaring equation (A-7) and solving for L gives

$$L = \frac{B^2}{60\,z^* + 2B} \tag{A-8}$$

where

$$z^* = \frac{\Delta z}{\Delta \ln z}\ . \tag{A-9}$$

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